

**Final Technical Report for  
NASA Grant NAG5-8938  
Magnetic Fluctuations in the Jovian Magnetosphere  
0/15/00 - 01/14/02  
Principal Investigator: C. T. Russell**

## **1. Introduction**

The engine that drives the jovian magnetosphere is the mass added to the Io ion torus, accelerated to corotational velocities by field-aligned currents that couple the Io torus to the jovian ionosphere. The mass of the torus builds up to an amount that the magnetic forces cannot contain and the plasma, first slowly and then more rapidly, drifts outward. Numerous authors have treated this problem based first on the observations of the Pioneer 10 and 11 flybys; then on Voyager 1 and 2, and Ulysses; and finally most recently the Galileo orbiter (e.g. Hill et al., 1983; Vasyliunas, 1983; Kivelson et al., 1997a; Russell et al., 2000). The initial observations revealed the now familiar magnetodisk, in which the field above and below the magnetic equator became quite radial in orientation and much less dipolar. The Galileo observations show this transformation to occur on average at  $24 R_J$  and to often be quite abrupt (Russell et al., 1999a). These observations are consistent with outward transport of magnetized plasma that moves ever faster radially until about  $50 R_J$  on the nightside where the field lines stretch to the breaking point, reconnection occurs, and plasma and field islands are transported down the tail ultimately removing the mass from the magnetosphere that Io had deposited deep in the inner torus (Russell et al., 1998). The reconnection process creates empty flux tubes connected to Jupiter that are buoyant and thought to float inward and replace the flux carried out with the torus plasma (Russell et al., 2000).

As described above, the jovian magnetosphere could very well be in a state of steady laminar circulation, but indeed it is not. The process is very unsteady and the wave levels can be very intense (Russell et al., 1999b). The existence of these waves in turn can lead to processes that compete with the radial circulation pattern in removing plasma from the system. These waves can scatter particles so that they precipitate into the ionosphere. This process should be important in the Io torus where the atmospheric loss cone is relatively large and becomes less important as the loss cone decreases in size with radial distance. However, the Io torus is relatively quiet compared to the region outside the torus and it is not obvious without studying this scattering carefully whether the loss in the torus or out of the torus is greater and whether it can act rapidly enough to compete with the radial transport of ions to the tail in the life cycle of the mass added at Io. Closer to Io the ion cyclotron waves are most intense and possibly are associated with the losses in the Io flux tube. The waves are also diagnostic of both the Io atmospheric composition and the size and strength of the massloading process.

## **References**

- Hill T. W., A. J. Dessler, and C. K. Goertz, Magnetospheric models, in *Physics of the Jovian Magnetosphere*, edited by A.J. Dessler, pp. 353-394, Cambridge Univ. Press, New York, 1983.

- Kivelson, M. G., K. K. Khurana, C. T. Russell, and R. J. Walker, Intermittent short-duration magnetic field anomalies in the Io torus: Evidence for plasma interchange, *Geophys. Res. Lett.*, 24, 2127-2130, 1997a.
- Russell, C. T., K. K. Khurana, D. E. Huddleston, and M. G. Kivelson, Localized reconnection in the near Jovian magnetotail, *Science*, 280, 1061-1064, 1998.
- Russell, C. T., D. E. Huddleston, K. K. Khurana and M. G. Kivelson, Observations at the inner edge of the Jovian current sheet: evidence for a dynamic magnetosphere, *Planet. Space Sci.*, 47, 521-527, 1999a.
- Russell, C. T., D. E. Huddleston, K. K. Khurana and M. G. Kivelson, The fluctuating magnetic field in the middle jovian magnetosphere: Initial Galileo observations, *Planet. Space Sci.*, 47, 133-142, 1999b.
- Russell, C. T., M. G. Kivelson, K. K. Khurana and D. E. Huddleston, Circulation and dynamics in the jovian magnetosphere, *Adv. Space Res.*, 26(10), 1671-1676, 2000.
- Vasyliunas, V. M., Plasma distribution and flow, in *Physics of the Jovian Magnetosphere*, edited by A. J. Dessler, pp. 395-453, Cambridge University Press, London, 1983.

## 2. Progress to Date

Work in this effort concentrated on three areas: the region near Io where the ion cyclotron waves are found, the waves more distant from Io that affect the scattering of these ions as they travel outward from the Io orbit to eventually partake in the reconnection processes in the near tail; and the region in the near tail where ions became separated from the magnetic field. The study of the waves near Io was advanced greatly with the availability of data on passes: I24, I25, I27, I31 and I32. The first of these produced an immediate surprise observation; waves at the  $\text{SO}^+$  gyrofrequency. These waves showed that SO was present in the Io upper atmosphere. A paper was prepared for *Science* and accepted [3-1]. When the data from I25 and I27 became available it was evident that the atmosphere contained other constituents as well including S and possibly  $\text{H}_2\text{S}$ . These results were submitted to the JGR Planets special issue on Io [3-19]. A detailed study of the amplitude of the waves with Io orbital phase showed that the amplitude varied with Io's location being strongest at magnetospheric noon when the dayside of Io was on the anti-Jupiter side of Io [3-10]. This work submitted to the JGR Space Physics special issue on Io also indicates that the reason for the appearance of SO on I24, I25 and I27 was that SO is a major constituent of the night time Io atmosphere and that the night local time sector requires some exposure to the anti-Jupiter side of Io for SO to escape. Together these papers and papers 3-14 and 3-15 show that the massloading process at Io depends very much on where Io is around Jupiter and that the massloading region has an unusual shape. It extends inward and outward from Io and downstream in the co-rotation direction but not upstream. Moreover, when combined with Voyager 1's lack of detection of ion cyclotron waves, this suggests that the massloading occurs in a thin disk. To understand this result we undertook some particle tracing experiment with a very simple model. We assumed that, in the region in which the torus plasma flowed most closely to Io, ions were created from the exosphere, accelerated in the planetary corotation electric field and moved in the well known cycloidal trajectory. However, because the ions were still in a region of fairly dense neutrals, they charge exchanged back into neutrals keeping their accelerated speeds. They then sped across the field lines inward, outward, and downstream from Io later to be ionized and become more permanent members of the torus plasma [3-11, 3-16]. This simple mechanism can reproduce the region of ion cyclotron wave

growth and produces a cool (but not cold) inner torus plasma. It also predicts variations in the mass addition process with Io orbital phase similar to that observed. We view this as a major accomplishment and one that was not foreseen when we wrote the original proposal.

We also continued to explore the wave properties and their possible causes. We looked again at the IO flyby [3-4, 3-5] and showed that the waves propagated not just along the field but at some times large angles to the magnetic field. The wave amplitude can also be used to estimate the massloading rate. Examination of the dispersion relation for ion cyclotron waves revealed the situations under which off-angle propagation can occur and the effect of one heavy ion population on the growth rate of ion cyclotron waves at the gyrofrequency of another ion [3-9, 3-12, 3-15]. The ion cyclotron waves on I31 also provided a remote sensing of the minimum magnetic field in the wake behind Io [4-19].

These results were also presented at the Spring 2000 AGU meeting [4-1, 4-2, 4-3, 4-4], the COSPAR meeting [4-6, 4-7] at the DPS meeting [4-12], the Fall AGU [4-14], the 2001 EGS meeting [4-15], the Spring 2001 AGU meeting [4-17] at the DPS meeting [4-18].

The second thrust of our effort was to examine the waves far from Io where the particles could be scattered in pitch angle and leave the magnetic field line in the atmospheric loss cone. Waves that could cause such scattering were discovered in the middle magnetosphere of Jupiter [3-2]. In a paper originally prepared for the Magnetospheres of the Outer Planet Meeting and later modified when funding for this effort arrived we examined the rate of scattering produced by these waves [3-20]. This paper shows that these waves are certainly active and could precipitate particles over a long enough residence time but that the plasma moves through the middle magnetosphere too rapidly to be seriously depleted. These results were also reported at the COSPAR meeting [4-10]. We examined the changes in the magnetosphere that might affect the extremely high-energy particles [3-18, 4-19].

Finally, we have examined the larger scale fluctuations associated with substorm like phenomena in the outer magnetosphere of Jupiter [3-3, 3-6]. This process separates the magnetic flux and the mass loaded ions enabling the jovian magnetosphere to achieve a steady state, albeit a dynamic study state. The magnetic flux emptied of ions then returns to the inner magnetosphere. Evidence of this has been found in the form of narrow depleted flux tubes [3-7, 3-17]. Lastly the stability of the jovian "ring current" has been examined [3-13]. These results were also presented at meetings [4-8, 4-11, 4-16].

### **3. Papers Published in Journals and Books**

1. C. T. Russell, and M. G. Kivelson, Detection of SO in Io's exosphere, Science, 287, 1998-1999, 2000.
2. C. T. Russell, D. E. Huddleston, K. K. Khurana, and M. G. Kivelson, Waves and fluctuations in the jovian magnetosphere, Adv. Space Res., 26(10), 1489-1498, 2000.
3. C. T. Russell, K. K. Khurana, M. G. Kivelson, and D. E. Huddleston, Substorms at Jupiter: Galileo observations of transient reconnection in the near tail, Adv. Space Res., 26(10),

1499-1504, 2000.

4. C. T. Russell, and D. E. Huddleston, Ion-cyclotron waves at Io, Adv. Space Res., 26(10), 1505-1511, 2000.
5. D. E. Huddleston, R. J. Strangeway, X. Blanco-Cano, C. T. Russell, M. G. Kivelson, and K. K. Khurana, Io-Jupiter interaction: Waves generated by pickup ions, Adv. Space Res., 26(10), 1513-1518, 2000.
6. C. T. Russell, M. G. Kivelson, K. K. Khurana, and D. E. Huddleston, Circulation and dynamics in the jovian magnetosphere, Adv. Space Res., 26(10), 1671-1676, 2000.
7. C. T. Russell, M. G. Kivelson, W. S. Kurth, and D. A. Gurnett, Implications of depleted flux tubes in the jovian magnetosphere, Geophys. Res. Lett., 27, 3133-3136, 2000.
8. C. T. Russell, The dynamics of planetary magnetospheres, Planet. Space Sci., 49, 1005-1030, 2001.
9. X. Blanco-Cano, C. T. Russell, D. E. Huddleston, and R. J. Strangeway, Ion cyclotron waves near Io, Planet. Space Sci., 49, 1125-1136, 2001.
10. C. T. Russell, Y. L. Wang, X. Blanco-Cano, and R. J. Strangeway, The Io mass-loading disk: Constraints provided by ion cyclotron wave observations, J. Geophys. Res., 106, 26,233-26,242, 2001.
11. Y. Wang, C. T. Russell, and J. Raeder, The Io mass-loading disk: Model calculations, J. Geophys. Res., 106, 26,243-26,260, 2001.
12. X. Blanco-Cano, C. T. Russell, and R. J. Strangeway, The Io mass-loading disk: Wave dispersion analysis, J. Geophys. Res., 106, 26,261-26,275, 2001.
13. C. T. Russell, Z. J. Yu, K. K. Khurana, and M. G. Kivelson, Magnetic field changes in the inner magnetosphere of Jupiter, Adv. Space Res., 28(6), 897-902, 2001.
14. C. T. Russell, and M. G. Kivelson, Identification of sulfur compounds in Io's exosphere, Adv. Space Res., 28(10), 1463-1467, 2001.
15. X. Blanco-Cano, C. T. Russell, R. J. Strangeway, M. G. Kivelson, and K. K. Khurana, Galileo observations of ion cyclotron waves in the Io torus, Adv. Space Res., 28(10), 1469-1474, 2001.
16. C. T. Russell, X. Blanco-Cano, R. J. Strangeway, Y. L. Wang, and J. Raeder, A mechanism for the production of disk-shaped neutral source cloud at Io, Adv. Space Res., 28(10), 1475-1479, 2001.
17. C. T. Russell, M. G. Kivelson, W. S. Kurth, and D. A. Gurnett, Depleted magnetic flux tubes

as probes of the Io torus plasma, Adv. Space Res., **28**(10), 1489-1493, 2001.

18. C. T. Russell, P. D Fieseler, D. Bindshadler, Z. J. Yu, S. P. Joy, K. K. Khurana, and M. G. Kivelson, Large scale changes in the highly energetic charged particles in the region of the Io torus, Adv. Space Res., **28**(10), 1495-1500, 2001.
19. C. T. Russell, and M. G. Kivelson, Evidence for sulfur dioxide, sulfur monoxide, and hydrogen sulfide in the Io exosphere, J. Geophys. Res., **106**, 33,267-33,272, 2001.
20. C. T. Russell, X. Blanco-Cano, and R. J. Strangeway, Ultra-low-frequency waves in the Jovian magnetosphere: causes and consequences, Planet. Space Sci., **49**, 291-301, 2001.

#### **4. Contributed Papers at Meetings**

1. C. T. Russell, X. Blanco-Cano, R. J. Strangeway and M. G. Kivelson, The Io mass loading disk: Inferences from Ion cyclotron waves, presented at the AGU Spring Meeting (abstract) *Eos. Trans., AGU*, **81**(19), Suppl., S289, 2000.
2. Y. L. Wang, C. T. Russell and J. Raeder, The Io mass loading disk: Formation by corotational electric field acceleration followed by charge exchange, presented at the AGU Spring Meeting (abstract) *Eos. Trans., AGU*, **81**(19), Suppl., S289, 2000.
3. X. Blanco-Cano, C. T. Russell and R. J. Strangeway, The Io mass loading disk: Ion cyclotron waves generation, presented at the AGU Spring Meeting (abstract) *Eos. Trans., AGU*, **81**(19), Suppl., S289, 2000.
4. C. T. Russell and M. G. Kivelson, Detection of SO in Io's Exosphere, presented at the AGU Spring Meeting (abstract) *Eos. Trans., AGU*, **81**(19), Suppl., S291, 2000.
5. M. G. Kivelson, K. K. Khurana, J. A. Linker, J. Walker, C. T. Russell, M. Volwerk and C. Zimmer, Io's magnetic field and plasma interactions, presented at the AGU Spring Meeting (abstract) *Eos. Trans., AGU*, **81**(19), Suppl., S291, 2000.
6. X. Blanco-Cano, C. T. Russell, R. J. Strangeway, M. G. Kivelson and K. K. Khurana, Galileo observations of ion cyclotron waves in the Io torus, presented at the 33<sup>rd</sup> COSPAR Scientific Assembly, Warsaw, July, 2000.
7. C. T. Russell, X. Blanco-Cano, R. J. Strangeway and Y. L. Wang, Evidence for a disk-shaped neutral source cloud at Io, presented at the 33<sup>rd</sup> COSPAR Scientific Assembly, Warsaw, July, 2000.
8. C. T. Russell, M. G. Kivelson, W. S. Kurth and D. A. Gurnett, Empty magnetic flux tubes as probes of the ion temperature of the Io torus, presented at the 33<sup>rd</sup> COSPAR Scientific Assembly, Warsaw, July, 2000.
9. C. T. Russell, P. D. Fieseler, D. Bindshadler, Z. J. Yu, S. P. Joy, K. K. Khurana and M. G.

Kivelson, Large scale changes in the highly relativistic charged particles in the region of the Io torus, presented at the 33<sup>rd</sup> COSPAR Scientific Assembly, Warsaw, July, 2000.

10. C. T. Russell, X. Blanco-Cano, R. J. Strangeway, The fluctuating magnetic field of the middle magnetosphere of Jupiter, presented at the 33<sup>rd</sup> COSPAR Scientific Assembly, Warsaw, July, 2000.
11. C. T. Russell, Z. J. Yu, K. K. Khurana and M.G. Kivelson, Magnetic field changes in the inner magnetosphere of Jupiter, presented at the 33<sup>rd</sup> COSPAR Scientific Assembly, Warsaw, July, 2000.
12. Y. L. Wang, C. T. Russell, J. Raeder, and M. G. Kivelson, Variability of the composition of Io's exosphere deduced from the spectrum of ion cyclotron waves, presented at the 32<sup>nd</sup> DPS Meeting, Pasadena, CA, (abstract) BAAS, 32, 1058, 2000.
13. Y. L. Wang, C. T. Russell, and J. Raeder, A three step model of the mass loading of the Io torus using fast neutrals, presented at the AGU Fall Meeting (abstract), *Eos. Trans., AGU*, 81(48), F795, 2000.
14. X. Blanco-Cano, C. T. Russell, and R. J. Strangeway, Ion cyclotron waves near Io: Dispersion analysis, presented at European Geophysical Society meeting, Nice, March 2001.
15. C. T. Russell, Y. L. Wang, J. Raeder, and X. Blanco-Cano, Ion cyclotron waves near Io: Implications for Io's atmosphere and for the creation of the Io torus, presented at European Geophysical Society meeting, Nice, March 2001.
16. C. T. Russell and M. G. Kivelson, Depleted flux tubes as a probe of the Io plasma torus, presented at European Geophysical Society meeting, Nice, March 2001.
17. X. Blanco-Cano, C. T. Russell and R. J. Strangeway, Growth of ion cyclotron waves in the Io torus, presented at the Spring National AGU meeting (abstract), *Eos. Trans. AGU*, 82(20), S355, 2001.
18. X. Blanco-Cano, C. T. Russell, R. J. Strangeway and M. G. Kivelson, Ion cyclotron waves observed near Io on Galileo flyby I31, presented at the 33<sup>rd</sup> DPS Meeting, New Orleans, November 2001 (abstract) BAAS, 33, 1085, 2001.
19. C. T. Russell, X. Blanco-Cano, R. J. Strangeway and M. G. Kivelson, Ion cyclotron waves at Io on orbit I31, presented at the Fall AGU meeting (abstract) *Eos. Trans. AGU*, 82(47), Fall Meeting Suppl., Abstract P11A-05, F684, 2001.